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# Search for heavy long-lived charged $R$ -hadrons with the ATLAS detector in $3.2 \text{ fb}^{-1}$ of proton–proton collision data at $\sqrt{s} = 13 \text{ TeV}$



The ATLAS Collaboration <sup>\*</sup>

## ARTICLE INFO

### Article history:

Received 17 June 2016

Received in revised form 11 July 2016

Accepted 15 July 2016

Available online 19 July 2016

Editor: W.-D. Schlatter

## ABSTRACT

A search for heavy long-lived charged  $R$ -hadrons is reported using a data sample corresponding to  $3.2 \text{ fb}^{-1}$  of proton–proton collisions at  $\sqrt{s} = 13 \text{ TeV}$  collected by the ATLAS experiment at the Large Hadron Collider at CERN. The search is based on observables related to large ionisation losses and slow propagation velocities, which are signatures of heavy charged particles travelling significantly slower than the speed of light. No significant deviations from the expected background are observed. Upper limits at 95% confidence level are provided on the production cross section of long-lived  $R$ -hadrons in the mass range from 600 GeV to 2000 GeV and gluino, bottom and top squark masses are excluded up to 1580 GeV, 805 GeV and 890 GeV, respectively.

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## 1. Introduction

Heavy long-lived particles (LLP) are predicted in a range of theories extending the Standard Model (SM) in an attempt to address the hierarchy problem [1]. These theories include supersymmetry (SUSY) [2–7], which allows for long-lived charged sleptons ( $\tilde{\ell}$ ), squarks ( $\tilde{q}$ ), gluinos ( $\tilde{g}$ ) and charginos ( $\tilde{\chi}_1^\pm$ ) in models that either violate [8–10] or conserve [11–17]  $R$ -parity.

Heavy long-lived charged particles can be produced at the Large Hadron Collider (LHC). A search for composite colourless states of squarks or gluinos together with SM quarks or gluons, called  $R$ -hadrons [11], is presented in this Letter. The search exploits the fact that these particles are expected to propagate with a velocity,  $\beta = v/c$ , substantially lower than one and to exhibit a specific ionisation energy loss,  $dE/dx$ , larger than that for any charged SM particle. Similar searches have been performed previously by the ATLAS and CMS Collaborations [18,19] using data samples from Run 1 at the LHC. No excesses of events above the expected backgrounds were observed, and lower mass limits were set at 95% confidence level (CL) around 1300 GeV for gluino  $R$ -hadrons.

$R$ -hadrons can be produced in  $pp$  collision as either charged or neutral states, and can be modified to a state with different charge by interactions with the detector material [20,21], arriving as neutral, charged or doubly charged particles in the muon spectrometer (MS) of the ATLAS detector. This search does not use information from the MS and follows the “MS-agnostic”  $R$ -hadron search approach in Ref. [18]. This strategy avoids assumptions

about  $R$ -hadron interactions with the detector, especially in the calorimeters, and is sensitive to scenarios in which  $R$ -hadrons decay or become neutral (via parton exchange with the detector material in hadronic interactions) before reaching the MS.

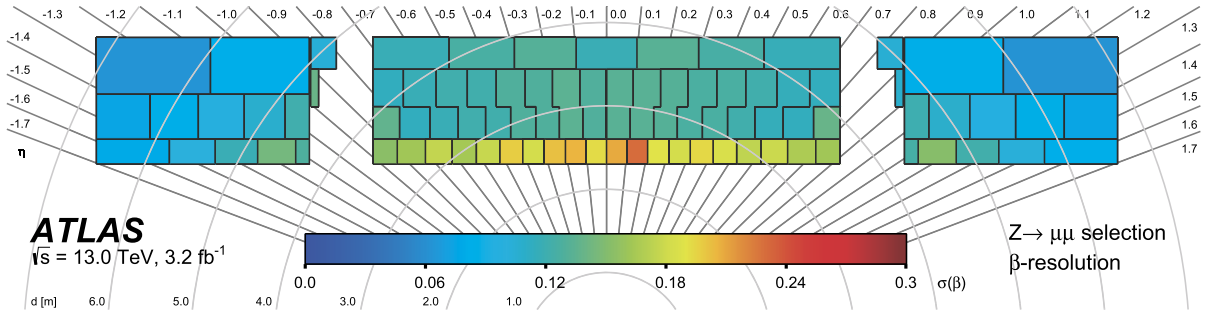
## 2. ATLAS detector

The ATLAS detector [22] is a multi-purpose particle-physics detector consisting of an inner detector (ID) immersed in an axial magnetic field to reconstruct trajectories of charged particles, calorimeters to measure the energy of particles that interact electromagnetically or hadronically and a MS within a toroidal magnetic field to provide tracking for muons. With near  $4\pi$  coverage in solid angle,<sup>1</sup> the ATLAS detector is able to deduce the missing transverse momentum,  $\vec{p}_T^{\text{miss}}$ , associated with each event. The components of particular importance to this search are described in more detail below.

The ID consists of two distinct silicon detectors and a straw tracker, which jointly provide good momentum measurements for charged tracks. The innermost part of the ID, a silicon pixel detector, typically provides four or more precision measurements for each track in the region  $|\eta| < 2.5$  at radial distances  $3.4 < r < 13 \text{ cm}$  from the LHC beam line. All pixel layers are similar, except

<sup>1</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the  $z$ -axis coinciding with the axis of the beam pipe. The  $x$ -axis points from the IP to the centre of the LHC ring, and the  $y$ -axis points upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ .

<sup>\*</sup> E-mail address: [atlas.publications@cern.ch](mailto:atlas.publications@cern.ch).

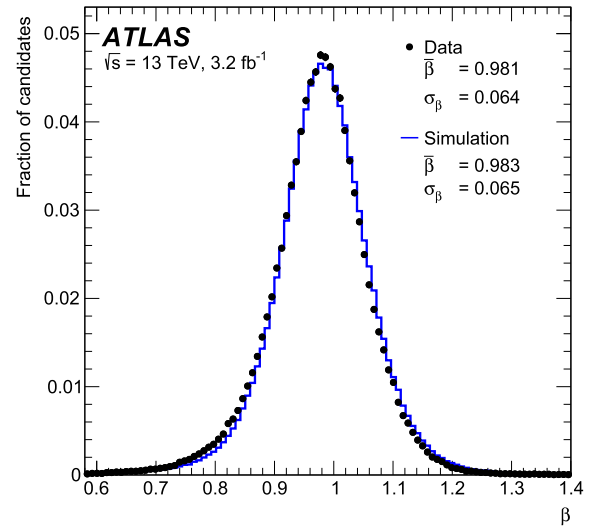


**Fig. 1.** Resolution of  $\beta$  for different cells in the ATLAS tile calorimeter obtained from a  $Z \rightarrow \mu\mu$  selection in data. The final  $\beta$  measurement is a weighted average of the  $\beta$  measurements in the cells traversed by the candidate.

the innermost Insertable B-Layer (IBL) [23], which has a smaller pixel size and a reduced thickness, but also 4-bit instead of 8-bit encoding and hence poorer charge resolution than the other pixel layers. The charge released by the passage of a charged particle is rarely contained within a single silicon pixel, and a neural network algorithm [24] is used to form clusters from the single pixel charges. For each cluster in the pixel detector a  $dE/dx$  estimate can be provided, from which an overall  $dE/dx$  measurement is calculated as a truncated mean to reduce the effect of the tail of the Landau distribution, by disregarding the one or two largest measurements [25]. Radiation sensitivity of the IBL electronics results in the measured  $dE/dx$  drifting over time. This effect is corrected by applying a dedicated time-dependent ionisation correction of 1.2% on average. The mean and RMS of the  $dE/dx$  measurement for a minimum-ionising particle are  $1.12 \text{ MeVg}^{-1} \text{cm}^2$  and  $0.13 \text{ MeVg}^{-1} \text{cm}^2$ , respectively, while the distribution extends to higher  $dE/dx$  values, due to the remnants of the Landau tail.

The ATLAS calorimeter in the central detector region consists of an electromagnetic liquid-argon calorimeter followed by a hadronic tile calorimeter. The estimation of  $\beta$  from time-of-flight measurements relies on timing and distance information from tile-calorimeter cells crossed by the extrapolated candidate track in three radial layers in the central barrel as well as an extended barrel on each side, as illustrated in Fig. 1. To reduce effects of detector noise, only cells in which the associated particle has deposited a minimum energy  $E_{\text{min,cell}} = 500 \text{ MeV}$  are taken into account. The time resolution depends on the energy deposited in the cell and also the layer type and thickness of the cell.

A series of calibration techniques is applied to achieve optimal performance, using a  $Z \rightarrow \mu\mu$  control sample. Muons on average deposit slightly less energy than expected from signal, but variations sufficiently cover the relevant range. First, a common time shift is applied for each short period of data taking (run) followed by five additional cell-by-cell  $\beta$  corrections. A geometry-based cell correction is introduced to minimise the  $\eta$  dependence of  $\beta$  within each individual cell. This is done by taking into account the actual trajectory ( $\eta$  and path length) of the extrapolated track in each calorimeter cell, to recalculate the distance-of-flight, instead of using the centre of the cell, as done in previous ATLAS searches (e.g. in [18]). The effect is most prominent at the edges of the largest cells at high  $|\eta|$  with shifts of up to 0.05 in  $\beta$ , and almost negligible for the cells at low  $|\eta|$ . An additional correction, linear in  $|\eta|$  and only applied in simulation, is added to account for a timing mismodelling due to an imperfect simulation. This correction is again most prominent for the cells at high  $|\eta|$  with shifts up to 0.1 in  $\beta$ . The Optimal Filtering Algorithm (OFA) [26] used for the read-out of the tile calorimeter cells is optimised for in-time signals and introduces a bias towards lower values of  $\beta$  in the measured cell



**Fig. 2.** Distributions of  $\beta$  for data and simulation after a  $Z \rightarrow \mu\mu$  selection. The values given for the mean and width are taken from Gaussian functions matched to data and simulation.

time of late-arriving particles. To compensate for this bias for late-arriving particles, a correction is estimated from a fit to simulated late signals. Cell times larger than 25 ns are discarded, to limit the size of the required correction. The size of the correction is up to 0.05 in  $\beta$ . A cell-time smearing is applied to adjust the cell-time resolution in simulation to that observed in data. The uncertainty in the single  $\beta$  measurements is scaled up by about 12%, based on the requirement that the pull distribution  $(\beta - \beta_{\text{true}})/\sigma_\beta$  be a unit Gaussian. Finally the  $\beta$  associated with the particle is estimated as a weighted average, using the  $\beta$  measurement in each traversed cell and its uncertainty,  $\sigma_\beta$ .

After all calibrations, the single cell-time resolution ranges from 1.3 ns in cells at large radii to 2.5 ns in cells at small radii. The distances from the nominal interaction point (IP) to the cell centres are 2.4 m to 3.6 m (4.2 m to 5.7 m) at  $|\eta| \sim 0$  ( $|\eta| \sim 1.25$ ). This in turn results in a resolution of 0.06 to 0.23 in  $\beta$ , as shown in Fig. 1. The larger cells at large radii have a better resolution due to the higher energy deposits and their increased distance from the IP.

As described in Section 5, the expected  $\beta$  distribution for the background is determined from data. However, the  $\beta$  distribution for the  $R$ -hadron signal is obtained from simulation. Fig. 2 shows the  $\beta$  distributions obtained for both data and simulation for a control sample of  $Z \rightarrow \mu\mu$  events that is used to validate the  $\beta$  measurement. Good agreement between data and simulation supports the use of the simulation to predict the behaviour expected for the  $R$ -hadron signal.

**Table 1**Final selection requirements as a function of the simulated  $R$ -hadron mass.

Simulated $R$ -hadron mass [GeV]	600	800	1000	1200	1400	1600	1800	2000
$\beta\gamma^{\max}$	1.35	1.35	1.35	1.35	1.35	1.15	1.15	1.15
$\beta^{\max}$	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
$m_{\beta\gamma}^{\min}$	350	450	500	575	650	675	750	775
$m_{\beta}^{\min}$	350	450	500	575	650	675	750	775

### 3. Data and simulated events

The work presented in this Letter is based on  $3.2 \text{ fb}^{-1}$  of  $pp$  collision data collected in 2015 at a centre-of-mass energy  $\sqrt{s} = 13 \text{ TeV}$ . Reconstructed  $Z \rightarrow \mu\mu$  events in data and simulation are used for timing resolution studies. Simulated signal events are used to study the expected signal behaviour.

$R$ -hadron signal events are generated with gluino (bottom-squark and top-squark) masses from 600 GeV to 2000 GeV (600 GeV to 1400 GeV). Pair production of gluinos and squarks is simulated in PYTHIA 6.427 [27] with the AUET2B [28] set of tuned parameters for the underlying event and the CTEQ6L1 [29] parton distribution function (PDF) set, incorporating PYTHIA-specific specialised hadronisation routines [20,30,31] to produce final states containing  $R$ -hadrons. The masses of the other SUSY particles are set to very high values to ensure that their contribution to the production cross section is negligible. For a given sparticle mass the production cross section for gluino  $R$ -hadrons is typically an order of magnitude higher than for bottom-squark and top-squark  $R$ -hadrons. The probability for a gluino to form a gluon-gluino bound state is assumed, based on a colour-octet model, to be 10% [12]. The associated hadronic activity produced by the colour field of the sparticle typically only possesses a small fraction of the initial energy of the sparticle [12], which should therefore be reasonably isolated.

To achieve a more accurate description of QCD radiative effects, the PYTHIA events are reweighted to match the transverse-momentum distribution of the gluino-gluino or squark-squark system to that obtained in dedicated MG5\_aMC@NLO v2.2.3.p0 [32] events, as MG5\_aMC@NLO can produce additional QCD initial-state radiation (ISR) jets as part of the hard process, while PYTHIA only includes showering to add jets to the event.

All events pass through a full detector simulation [33], where interactions with matter are handled by dedicated GEANT4 [34] routines based on different scattering models: the model used to describe gluino (squark)  $R$ -hadron interactions is referred to as the generic (Regge) model [21]. The  $R$ -hadrons interact only moderately with the detector material, as most of the  $R$ -hadron momentum is carried by the heavy gluino or squark, which has little interaction cross section. Typically, the energy deposit in the calorimeters is less than 10 GeV.

All simulated events include a modelling of contributions from pile-up by overlaying minimum-bias  $pp$  interactions from the same (in-time pile-up) and nearby (out-of-time pile-up) bunch crossings, and are reconstructed using the same software used for collision data. Simulated events are reweighted so that the distribution of the expected number of collisions per bunch crossing matches that of the data.

### 4. Event selection

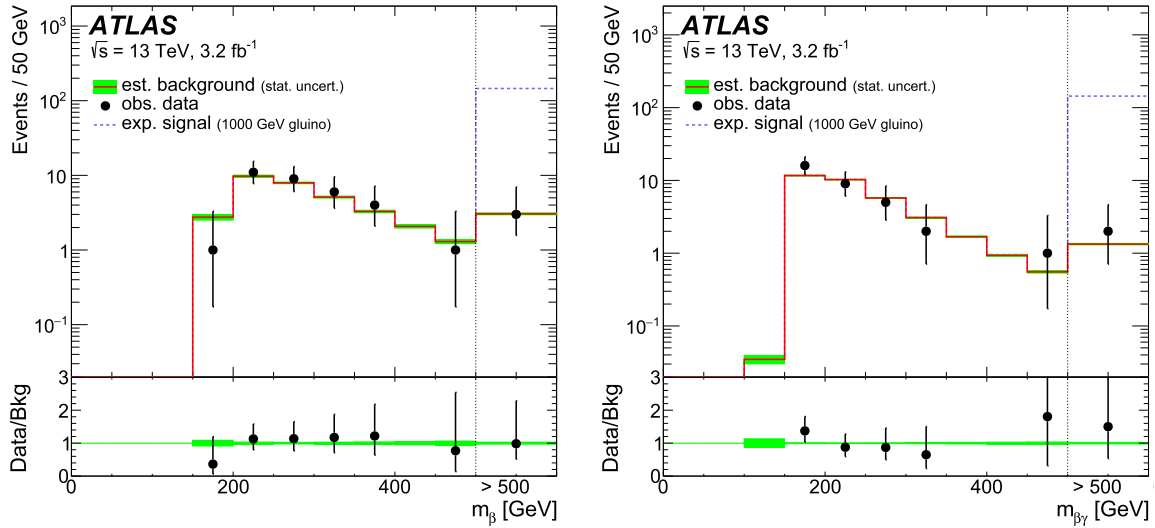
Events are selected online via a trigger based on the magnitude of the missing transverse momentum,  $E_T^{\text{miss}}$ . Large  $E_T^{\text{miss}}$  values are produced mainly when QCD initial-state radiation (ISR) boosts

the  $R$ -hadron system, resulting in an imbalance between ISR and  $R$ -hadrons whose momenta are not fully accounted for in the  $E_T^{\text{miss}}$  calculation. In particular, the adopted trigger imposes a threshold of 70 GeV on  $E_T^{\text{miss}}$  calculated solely from energy deposits in the calorimeters [35]. The signal efficiency of the  $E_T^{\text{miss}}$  trigger varies between 32% and 50%, depending on the mass and type of the  $R$ -hadron.

The offline event selection requires all relevant detector components to be fully operational; a primary vertex (PV) built from at least two well-reconstructed charged-particle tracks, each with a transverse momentum,  $p_T$ , above 400 MeV; and at least one  $R$ -hadron candidate track that meets the criteria specified below.

$R$ -hadron candidates are based on ID tracks with  $p_T > 50 \text{ GeV}$  and  $|\eta| < 1.65$ . Candidates must not be within  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$  of any jet with  $p_T > 50 \text{ GeV}$ , reconstructed using the anti- $k_t$  jet algorithm [36] with radius parameter set to 0.4. Furthermore, the candidates must not have any additional nearby ( $\Delta R < 0.2$ ) tracks with  $p_T > 10 \text{ GeV}$ . Tracks reconstructed with  $p > 6.5 \text{ TeV}$  are rejected as unphysical. To ensure a well reconstructed track, a minimum number of seven hits in the silicon detectors is required. Of these, at least two clusters used to measure  $dE/dx$  in the pixel detector are required, to ensure a good  $dE/dx$  measurement. Candidates with  $|z_0^{\text{PV}} \sin(\theta)| > 0.5 \text{ mm}$  or  $|d_0| > 2.0 \text{ mm}$  are removed, where  $d_0$  is the transverse impact parameter at the candidate track's point of closest approach to the IP and  $z_0^{\text{PV}}$  is the  $z$  coordinate of this point relative to the PV. To suppress background muons stemming from cosmic-ray interactions, candidates with direction  $(\eta, \phi)$  are rejected if an oppositely-charged track with almost specular direction, i.e. with  $|\Delta\eta| < 0.005$  and  $|\Delta\phi| < 0.005$  with respect to  $(-\eta, \pi - \phi)$ , is identified on the opposite side of the detector. In order to minimise the background from  $Z \rightarrow \mu\mu$  decays, candidates are rejected if they result in an invariant mass closer than 10 GeV to the mass of the  $Z$  boson when combined with the highest- $p_T$  muon candidate in the event. In addition to the above mentioned track-quality criteria, candidates must also satisfy observable-quality criteria, defined by an unambiguous  $\beta\gamma$  determination from the  $dE/dx$  value, estimated using an empirical relation (more details can be found in Ref. [37]), determined from low-momentum pions, kaons and protons [37], and a  $\beta$  measurement, with an uncertainty  $\sigma_\beta$  of less than 0.12. In the following,  $\beta\gamma$  refers to quantities derived from the  $dE/dx$  measurement in the silicon pixel detector and  $\beta$  refers to the time-of-flight-based measurement in the tile calorimeter.

After this initial selection, 226 107 of the approximately 36 million initially triggered data events as well as 10% to 15% of simulated signal events (the percentage increases with hypothesised mass) remain. Only the candidate with the largest  $p_T$  is used in events with multiple  $R$ -hadron candidates. The final signal selection, requiring a momentum above 200 GeV as well as criteria summarised in Table 1, is based on  $\beta\gamma$  and  $\beta$ , requiring  $\beta\gamma < 1.35$  ( $< 1.15$ ) for  $R$ -hadron masses up to (greater than) 1.4 TeV and  $\beta < 0.75$  in all cases. The signal region is defined in the  $m_{\beta\gamma}$ - $m_\beta$  plane for each  $R$ -hadron mass point, where  $m_{\beta\gamma}$  and  $m_\beta$  are extracted independently from the measurement of the momentum



**Fig. 3.** Data (black dots) and background estimates (red solid line) for  $m_\beta$  (left) and  $m_{\beta\gamma}$  (right) for the gluino  $R$ -hadron search (1000 GeV). The green shaded band illustrates the statistical uncertainty of the background estimate. The blue dashed lines illustrate the expected signal (on top of background) for the given  $R$ -hadron mass hypothesis. The black dashed vertical lines at 500 GeV show the mass selection and the last bin includes all entries/masses above. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

as well as  $\beta\gamma$  and  $\beta$ , respectively, via  $m = p/\beta\gamma$ . The minimum mass requirements,  $m_{\beta\gamma}^{\min}$  and  $m_\beta^{\min}$ , are set to correspond to a value about  $2\sigma$  below the nominal  $R$ -hadron mass value, given the mass resolution expected for the signal.

The total selection efficiency depends on the sparticle mass and varies between 9% and 15% for gluino and top-squark  $R$ -hadrons and 6% to 8% for bottom-squark  $R$ -hadrons. The lower efficiency for bottom squarks is expected, as  $R$ -hadrons are most likely produced in mesonic states, where those with down-type squarks tend to be neutral more often than those with up-type squarks, due to light-quark production ratios of  $u : d : s \approx 1 : 1 : 0.3$  [12] during hadronisation. The expected signal yield and efficiency, estimated background and observed number of events in data for the full mass range after the final selection are summarised in Table 3.

## 5. Background estimation

The background is evaluated in a data-driven manner. First, probability distribution functions (pdf) in the momentum, and also in the  $\beta$  and  $\beta\gamma$  values, are determined from data. These pdfs are produced from candidates in data, which have passed the initial selection mentioned earlier, but fall in sidebands of the signal region, as described below. Background distributions in  $m_\beta$  and  $m_{\beta\gamma}$  are obtained by randomly sampling the pdfs derived above and then using the equation  $m = p/\beta\gamma$ . These mass distributions, which are normalised to the data events outside the signal region (i.e. not passing both mass requirements of the hypothesis in question), are shown in Fig. 3 along with the data and expected signal for the 1000 GeV gluino  $R$ -hadron mass hypothesis.

Each  $R$ -hadron mass hypothesis has a different selection, and therefore corresponding individual background estimates are produced accordingly. The momentum pdf is produced from events that pass the momentum cut, but fail the  $\beta$  and  $\beta\gamma$  requirements in Table 1 for the chosen  $R$ -hadron mass hypothesis, but nonetheless have  $\beta < 1$  and  $\beta\gamma < 2.5$ . The  $\beta$  and  $\beta\gamma$  pdfs are produced by selecting events which pass the respective  $\beta$  and  $\beta\gamma$  selection and have momentum in the range  $50 \text{ GeV} < p < 200 \text{ GeV}$ . Since momentum is correlated with  $|\eta|$ , any correlation between  $|\eta|$  and  $\beta$  ( $\beta\gamma$ ) will lead to a correlation between momentum and

**Table 2**

Summary of all studied systematic uncertainties. Ranges indicate a dependency on the  $R$ -hadron mass hypothesis (from low to high masses).

Source	Relative uncertainty [%]
Theoretical uncertainty on signal	14–57
Uncertainty on signal efficiency	20–16
↳ Trigger efficiency	2
↳ QCD uncertainty (ISR, FSR)	14
↳ Pile-up	7–1
↳ Pixel $\beta\gamma$ measurement	1–3
↳ Calorimeter $\beta$ measurement	10–2
Luminosity	5
Uncertainties on background estimate	30–43

$\beta$  ( $\beta\gamma$ ), invalidating the background estimate. The size and impact of such correlations are reduced by determining the three pdfs in five equal-width bins of  $|\eta|$ . This procedure also ensures that different detector regions are treated separately.

## 6. Systematic uncertainties

The systematic uncertainties are obtained from data, whenever possible. The two major uncertainties for which this is not the case are cross sections and ISR, the latter being folded with the trigger efficiency curve obtained from data to produce the overall  $E_T^{\text{miss}}$  trigger efficiency. The individual contributions are outlined below and summarised in Table 2.

### 6.1. Theoretical cross sections

Signal cross sections are calculated to next-to-leading order in the strong coupling constant, including the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLO + NLL) [38–40]. The nominal cross section and the uncertainty are taken from an envelope of cross-section predictions using different PDF sets and factorisation and renormalisation scales, as described in Ref. [41]. This prescription results in an uncertainty of 14% (at 600 GeV) rising to 24% (at 1600 GeV) and to 32% (at 2000 GeV) for gluino  $R$ -hadrons and marginally larger values for squark  $R$ -hadrons.



**Table 3**

Expected signal yield ( $N_{\text{sig}}$ ) and efficiency (eff.), estimated background ( $N_{\text{bkg}}$ ) and observed number of events in data ( $N_{\text{obs}}$ ) for the full mass range after the final selection using  $3.2 \text{ fb}^{-1}$  of data. The stated uncertainties include both the statistical and systematic contribution.

<i>R</i> -hadron	Mass [GeV]	$N_{\text{sig}} \pm \sigma_{N_{\text{sig}}}$	eff. $\pm \sigma_{\text{eff}}$	$N_{\text{bkg}} \pm \sigma_{N_{\text{bkg}}}$	$N_{\text{obs}}$
Gluino	600	$3340 \pm 660$	$0.113 \pm 0.022$	$4.5 \pm 1.4$	3
	800	$500 \pm 110$	$0.105 \pm 0.022$	$1.75 \pm 0.53$	3
	1000	$143 \pm 28$	$0.137 \pm 0.027$	$1.23 \pm 0.37$	2
	1200	$36.5 \pm 6.4$	$0.133 \pm 0.023$	$0.77 \pm 0.25$	2
	1400	$12.2 \pm 2.2$	$0.151 \pm 0.028$	$0.54 \pm 0.19$	2
	1600	$3.6 \pm 0.6$	$0.140 \pm 0.023$	$0.185 \pm 0.071$	1
	1800	$1.00 \pm 0.18$	$0.11 \pm 0.02$	$0.138 \pm 0.057$	1
	2000	$0.378 \pm 0.063$	$0.12 \pm 0.02$	$0.126 \pm 0.053$	1
Bottom squark	600	$36.1 \pm 7.7$	$0.064 \pm 0.014$	$4.5 \pm 1.4$	3
	800	$6.6 \pm 1.5$	$0.073 \pm 0.016$	$1.75 \pm 0.53$	3
	1000	$1.62 \pm 0.33$	$0.082 \pm 0.017$	$1.23 \pm 0.37$	2
	1200	$0.407 \pm 0.077$	$0.079 \pm 0.015$	$0.77 \pm 0.25$	2
	1400	$0.122 \pm 0.024$	$0.082 \pm 0.016$	$0.54 \pm 0.19$	2
Top squark	600	$47.5 \pm 9.5$	$0.085 \pm 0.017$	$4.5 \pm 1.4$	3
	800	$10.7 \pm 2.3$	$0.118 \pm 0.025$	$1.75 \pm 0.53$	3
	1000	$2.70 \pm 0.52$	$0.137 \pm 0.026$	$1.23 \pm 0.37$	2
	1200	$0.72 \pm 0.13$	$0.141 \pm 0.025$	$0.77 \pm 0.25$	2
	1400	$0.216 \pm 0.039$	$0.146 \pm 0.027$	$0.54 \pm 0.19$	2

## 6.2. Signal efficiency

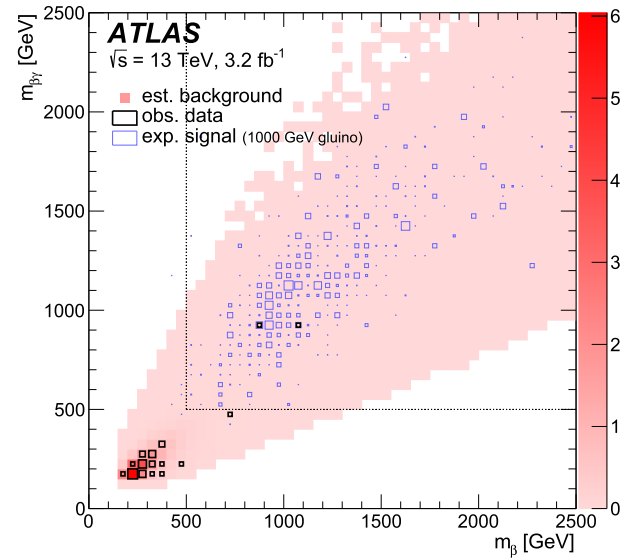
The  $E_{\text{T}}^{\text{miss}}$  trigger uses only calorimeter information to calculate  $E_{\text{T}}^{\text{miss}}$ , and has very low sensitivity to muons. Hence,  $Z \rightarrow \mu\mu$  events can be used for calibration and to study systematic errors. To evaluate the trigger efficiency, the trigger turn-on curve is obtained by fitting the measured efficiency vs.  $E_{\text{T}}^{\text{miss}}$  in  $Z \rightarrow \mu\mu$  events, in both data and simulation. These efficiency turn-on curves are then applied to the  $E_{\text{T}}^{\text{miss}}$  spectrum from simulated *R*-hadron events. The total uncertainty is estimated from four contributions: the relative difference between the efficiencies obtained using the fitted threshold curves from  $Z \rightarrow \mu\mu$  data and simulation, the differences in efficiency obtained from independent  $\pm 1\sigma$  variations in fit parameters relative to the unchanged turn-on-curve fit for both  $Z \rightarrow \mu\mu$  data and simulation and a 10% variation of the  $E_{\text{T}}^{\text{miss}}$  to assess the scale uncertainty. The  $E_{\text{T}}^{\text{miss}}$  trigger is estimated to contribute a total uncertainty of 2% to the signal efficiency.

To address a possible mismodelling of ISR, and hence  $E_{\text{T}}^{\text{miss}}$  in the signal events, half of the difference between the selection efficiency for the PYTHIA events and those reweighted with MG5\_aMC@NLO is taken as an uncertainty in the expected signal and found to be below 14% in all cases.

The uncertainty in the pile-up modelling in simulation is found to affect the signal efficiency by between 7% and 1%, decreasing as a function of the simulated *R*-hadron mass.

The systematic uncertainty in the  $\beta$  estimation is assessed by scaling the calorimeter-cell-time smearing of simulated events by  $\pm 10\%$ , varying by  $\pm 1\sigma$  the parameters of the linear fit to correct the remaining  $\eta$  dependence of the measured calorimeter time and by removing or doubling the cell-time correction introduced to correct the bias due to the OFA. The uncertainty is calculated as half the maximum variation in signal efficiency in all combinations divided by the average signal efficiency and is found to be between 10% and 2%, decreasing with simulated *R*-hadron mass.

The systematic uncertainty of the pixel  $\beta\gamma$  measurement is assessed by taking into account the differences between simulation and data, the remaining variation in the reconstruction of reference masses after a run-by-run correction of an observed drift of  $dE/dx$ , due to radiation sensitivity of the IBL electronics, and the stability of the  $dE/dx$ -based proton mass estimate over time. The impact on the signal efficiency is obtained by applying the variations corre-



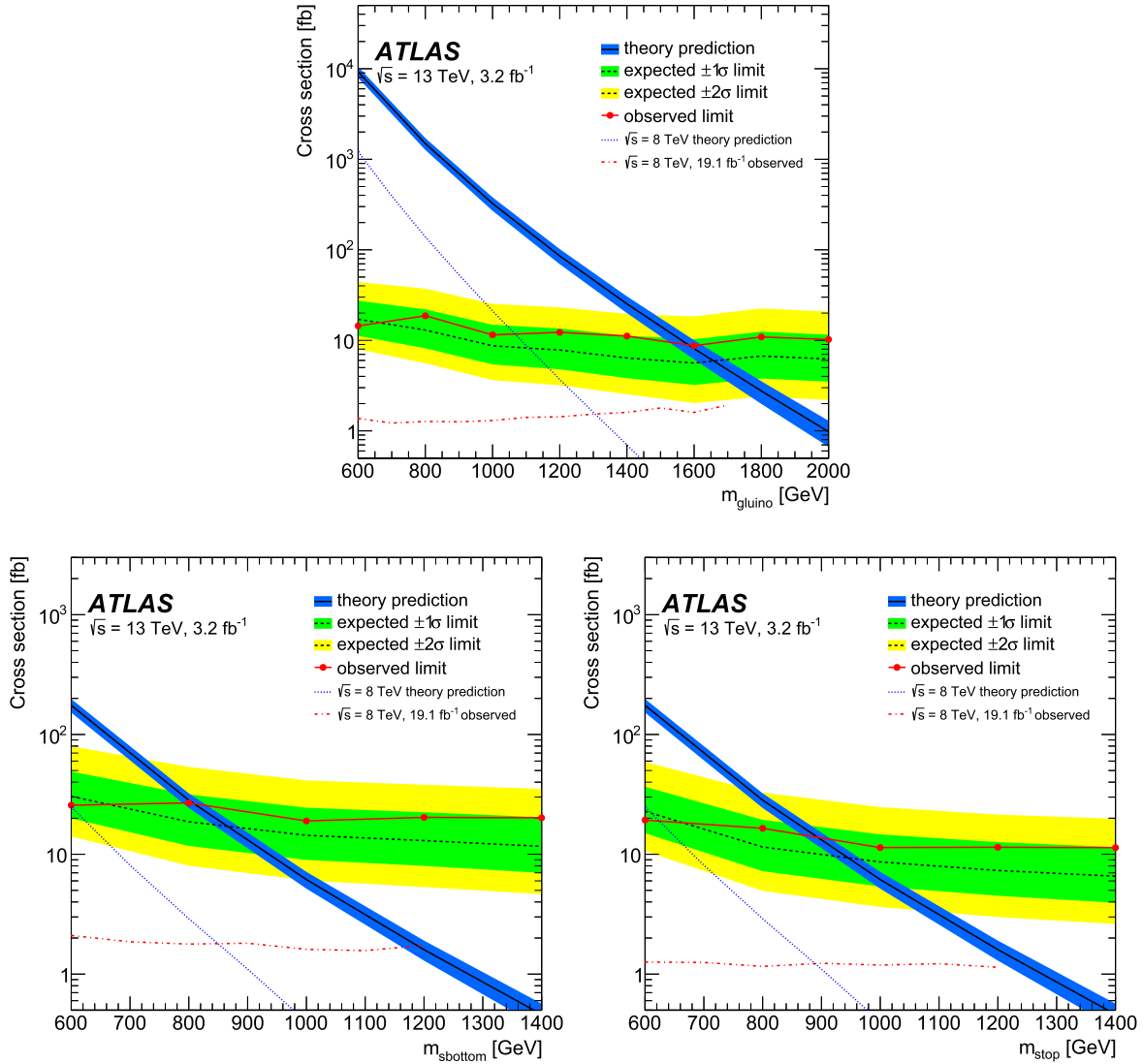
**Fig. 4.** Data (bold boxes) and background estimates (colour fill) for  $m_{\beta}$  vs.  $m_{\beta\gamma}$  for the gluino *R*-hadron search (1000 GeV). The blue thin-line boxes illustrate the expected signal (on top of background) for the given *R*-hadron mass hypothesis. The black dashed vertical/horizontal lines at 500 GeV show the mass selection (signal region in the top-right). Two events pass this selection. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sponding to the above-listed uncertainties independently and the overall size of these effects is found to be below 3% for any simulated *R*-hadron mass.

The uncertainty of the integrated luminosity is 5%, as derived following a methodology similar to that detailed in Ref. [42], from a calibration of the luminosity scale using  $x$ - $y$  beam-separation scans performed in August 2015.

## 6.3. Background estimation

The uncertainty in the background estimate is evaluated by varying both the number of  $|\eta|$  bins used when creating the  $p$ ,  $\beta$  and  $\beta\gamma$  pdfs and the requirements on the background selection region. The nominal number of  $|\eta|$  bins is varied between three and eight, while the requirements on observables are set



**Fig. 5.** Expected (dashed black line) and observed (solid red line) 95% CL upper limits on the cross section as a function of mass for the production of long-lived gluino (top), bottom-squark (bottom-left) and top-squark (bottom-right)  $R$ -hadrons. The theory prediction along with its  $\pm 1\sigma$  uncertainty is shown as a black line and a blue band, respectively. The observed 8 TeV Run-1 limit and theory prediction [18] are shown in dash-dotted and dotted lines, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to a *medium* ( $\beta < 0.975$ ,  $\beta\gamma < 2.45$  and  $60 \text{ GeV} < p < 190 \text{ GeV}$ ) and a *tight* ( $\beta < 0.95$ ,  $\beta\gamma < 2.4$  and  $70 \text{ GeV} < p < 180 \text{ GeV}$ ) selection. Uncertainties introduced by statistical fluctuations in the pdfs are estimated by repeating  $O(100)$  times the background estimation using pdfs with Poisson variations of the content in each bin.

The correction applied to high values of calorimeter cell times measured with the OFA is found to affect the background estimate by between 5% and 14%. Effects arising from the  $dE/dx$  measurement are assessed by using an analytical description to vary the shape of the high-ionisation tail and by changing the IBL ionisation correction by  $\pm 1\sigma$  and are found to be between 17% and 6%, decreasing with simulated  $R$ -hadron mass. The effect of signal contamination in the background estimation is studied by introducing the expected number of signal events into the data before building the background estimate and is found to be 10% at a simulated mass of 600 GeV, while negligible for higher masses, and is included in the overall uncertainty in the background estimate. The overall uncertainty in the background estimate is found to be 30% to 43%, rising with simulated  $R$ -hadron mass. Since the back-

ground is very small for high  $R$ -hadron masses ( $\geq 1400 \text{ GeV}$ ) the relatively large uncertainty does not affect the sensitivity in this region.

## 7. Results

The resulting mass distributions of events for the 1000 GeV gluino  $R$ -hadron mass hypothesis can be seen in Fig. 4. Two events with masses above 500 GeV pass the event selection for the 1000 GeV mass hypothesis, while only one of these events passes the event selection for the 1600 GeV mass hypothesis. However, as can be seen in Table 3, at no point in the examined mass range does this search exhibit any statistically significant excess of events above the expected background, which is  $1.23 \pm 0.37$  and  $0.185 \pm 0.071$  for the two above-mentioned mass hypotheses, respectively. Therefore, 95% CL upper limits are placed on the  $R$ -hadron production cross section, as shown in Fig. 5. These limits are obtained from the expected signal and the estimated background in the signal region and using a one-bin counting experiment applying the  $CL_s$  prescription [43].

Given the predicted theoretical cross sections, also shown in Fig. 5, the cross-section limits are translated into lower limits on  $R$ -hadron masses. Expected lower limits at 95% CL on the  $R$ -hadron masses of 1655 GeV, 865 GeV and 945 GeV for the production of long-lived gluino, bottom-squark and top-squark  $R$ -hadrons are derived, respectively. Corresponding observed lower mass limits at 95% CL for gluino, bottom-squark and top-squark  $R$ -hadrons are found to be 1580 GeV, 805 GeV and 890 GeV, respectively.

For comparison, the corresponding ATLAS Run-1 8 TeV lower limits at 95% CL on the mass of gluino, bottom-squark and top-squark  $R$ -hadrons [18] are also shown in Fig. 5.

## 8. Conclusion

A search for heavy long-lived particles in the form of composite colourless states of squarks or gluinos together with SM quarks and gluons, called  $R$ -hadrons, and taking advantage of both ionisation and time-of-flight measurements is presented in this Letter. The search uses  $3.2 \text{ fb}^{-1}$  of  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  collected by the ATLAS experiment at the LHC. No statistically significant excess of events above the expected background is found for any  $R$ -hadron mass hypothesis. Long-lived  $R$ -hadrons containing a gluino, bottom or top squark are excluded at 95% CL for masses up to 1580 GeV, 805 GeV and 890 GeV, respectively. These results substantially extend previous ATLAS and CMS limits from 8 TeV Run-1 data in case of gluino  $R$ -hadrons and are complementary to searches for SUSY particles which decay promptly.

## Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF

(Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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## The ATLAS Collaboration

M. Aaboud<sup>135d</sup>, G. Aad<sup>86</sup>, B. Abbott<sup>113</sup>, J. Abdallah<sup>64</sup>, O. Abdinov<sup>12</sup>, B. Abeloos<sup>117</sup>, R. Aben<sup>107</sup>, O.S. AbouZeid<sup>137</sup>, N.L. Abraham<sup>149</sup>, H. Abramowicz<sup>153</sup>, H. Abreu<sup>152</sup>, R. Abreu<sup>116</sup>, Y. Abulaiti<sup>146a,146b</sup>, B.S. Acharya<sup>163a,163b,a</sup>, L. Adamczyk<sup>40a</sup>, D.L. Adams<sup>27</sup>, J. Adelman<sup>108</sup>, M. Adersberger<sup>100</sup>, S. Adomeit<sup>100</sup>, T. Adye<sup>131</sup>, A.A. Affolder<sup>75</sup>, T. Agatonovic-Jovin<sup>14</sup>, J. Agricola<sup>56</sup>, J.A. Aguilar-Saavedra<sup>126a,126f</sup>, S.P. Ahlen<sup>24</sup>, F. Ahmadov<sup>66,b</sup>, G. Aielli<sup>133a,133b</sup>, H. Akerstedt<sup>146a,146b</sup>, T.P.A. Åkesson<sup>82</sup>, A.V. Akimov<sup>96</sup>, G.L. Alberghi<sup>22a,22b</sup>, J. Albert<sup>168</sup>, S. Albrand<sup>57</sup>, M.J. Alconada Verzini<sup>72</sup>, M. Aleksa<sup>32</sup>, I.N. Aleksandrov<sup>66</sup>, C. Alexa<sup>28b</sup>, G. Alexander<sup>153</sup>, T. Alexopoulos<sup>10</sup>, M. Alhroob<sup>113</sup>, B. Ali<sup>128</sup>, M. Aliev<sup>74a,74b</sup>, G. Alimonti<sup>92a</sup>, J. Alison<sup>33</sup>, S.P. Alkire<sup>37</sup>, B.M.M. Allbrooke<sup>149</sup>, B.W. Allen<sup>116</sup>, P.P. Allport<sup>19</sup>, A. Aloisio<sup>104a,104b</sup>, A. Alonso<sup>38</sup>, F. Alonso<sup>72</sup>, C. Alpigiani<sup>138</sup>, M. Alstamy<sup>86</sup>, B. Alvarez Gonzalez<sup>32</sup>, D. Álvarez Piqueras<sup>166</sup>, M.G. Alviggi<sup>104a,104b</sup>, B.T. Amadio<sup>16</sup>, K. Amako<sup>67</sup>, Y. Amaral Coutinho<sup>26a</sup>, C. Amelung<sup>25</sup>, D. Amidei<sup>90</sup>, S.P. Amor Dos Santos<sup>126a,126c</sup>, A. Amorim<sup>126a,126b</sup>, S. Amoroso<sup>32</sup>, G. Amundsen<sup>25</sup>, C. Anastopoulos<sup>139</sup>, L.S. Ancu<sup>51</sup>, N. Andari<sup>19</sup>, T. Andeen<sup>11</sup>, C.F. Anders<sup>59b</sup>, G. Anders<sup>32</sup>, J.K. Anders<sup>75</sup>, K.J. Anderson<sup>33</sup>, A. Andreazza<sup>92a,92b</sup>, V. Andrei<sup>59a</sup>, S. Angelidakis<sup>9</sup>, I. Angelozzi<sup>107</sup>, P. Anger<sup>46</sup>, A. Angerami<sup>37</sup>, F. Anghinolfi<sup>32</sup>, A.V. Anisenkov<sup>109,c</sup>, N. Anjos<sup>13</sup>, A. Annovi<sup>124a,124b</sup>, C. Antel<sup>59a</sup>, M. Antonelli<sup>49</sup>, A. Antonov<sup>98,\*</sup>, F. Anulli<sup>132a</sup>, M. Aoki<sup>67</sup>, L. Aperio Bella<sup>19</sup>, G. Arabidze<sup>91</sup>, Y. Arai<sup>67</sup>, J.P. Araque<sup>126a</sup>, A.T.H. Arce<sup>47</sup>, F.A. Arduh<sup>72</sup>, J-F. Arguin<sup>95</sup>, S. Argyropoulos<sup>64</sup>, M. Arik<sup>20a</sup>, A.J. Armbruster<sup>143</sup>, L.J. Armitage<sup>77</sup>, O. Arnaez<sup>32</sup>, H. Arnold<sup>50</sup>, M. Arratia<sup>30</sup>, O. Arslan<sup>23</sup>, A. Artamonov<sup>97</sup>, G. Artoni<sup>120</sup>, S. Artz<sup>84</sup>, S. Asai<sup>155</sup>, N. Asbah<sup>44</sup>, A. Ashkenazi<sup>153</sup>, B. Åsman<sup>146a,146b</sup>, L. Asquith<sup>149</sup>, K. Assamagan<sup>27</sup>, R. Astalos<sup>144a</sup>, M. Atkinson<sup>165</sup>, N.B. Atlay<sup>141</sup>, K. Augsten<sup>128</sup>, G. Avolio<sup>32</sup>, B. Axen<sup>16</sup>, M.K. Ayoub<sup>117</sup>, G. Azuelos<sup>95,d</sup>, M.A. Baak<sup>32</sup>, A.E. Baas<sup>59a</sup>, M.J. Baca<sup>19</sup>, H. Bachacou<sup>136</sup>, K. Bachas<sup>74a,74b</sup>, M. Backes<sup>148</sup>, M. Backhaus<sup>32</sup>, P. Bagiacchi<sup>132a,132b</sup>, P. Bagnaia<sup>132a,132b</sup>, Y. Bai<sup>35a</sup>, J.T. Baines<sup>131</sup>, O.K. Baker<sup>175</sup>, E.M. Baldin<sup>109,c</sup>, P. Balek<sup>171</sup>, T. Balestri<sup>148</sup>, F. Balli<sup>136</sup>, W.K. Balunas<sup>122</sup>, E. Banas<sup>41</sup>, Sw. Banerjee<sup>172,e</sup>, A.A.E. Bannoura<sup>174</sup>, L. Barak<sup>32</sup>, E.L. Barberio<sup>89</sup>, D. Barberis<sup>52a,52b</sup>, M. Barbero<sup>86</sup>, T. Barillari<sup>101</sup>, M-S Barisits<sup>32</sup>, T. Barklow<sup>143</sup>, N. Barlow<sup>30</sup>, S.L. Barnes<sup>85</sup>, B.M. Barnett<sup>131</sup>, R.M. Barnett<sup>16</sup>, Z. Barnovska<sup>5</sup>, A. Baroncelli<sup>134a</sup>, G. Barone<sup>25</sup>, A.J. Barr<sup>120</sup>, L. Barranco Navarro<sup>166</sup>, F. Barreiro<sup>83</sup>, J. Barreiro Guimarães da Costa<sup>35a</sup>, R. Bartoldus<sup>143</sup>, A.E. Barton<sup>73</sup>, P. Bartos<sup>144a</sup>, A. Basalae<sup>123</sup>, A. Bassalat<sup>117</sup>, R.L. Bates<sup>55</sup>, S.J. Batista<sup>158</sup>, J.R. Batley<sup>30</sup>, M. Battaglia<sup>137</sup>, M. Baue<sup>132a,132b</sup>, F. Bauer<sup>136</sup>, H.S. Bawa<sup>143,f</sup>, J.B. Beacham<sup>111</sup>, M.D. Beattie<sup>73</sup>, T. Beau<sup>81</sup>, P.H. Beauchemin<sup>161</sup>, P. Bechtel<sup>23</sup>, H.P. Beck<sup>18,g</sup>, K. Becker<sup>120</sup>, M. Becker<sup>84</sup>, M. Beckingham<sup>169</sup>, C. Becot<sup>110</sup>, A.J. Beddall<sup>20e</sup>, A. Beddall<sup>20b</sup>, V.A. Bednyakov<sup>66</sup>, M. Bedognetti<sup>107</sup>, C.P. Bee<sup>148</sup>, L.J. Beemster<sup>107</sup>, T.A. Beermann<sup>32</sup>, M. Beger<sup>27</sup>, J.K. Behr<sup>44</sup>, C. Belanger-Champagne<sup>88</sup>, A.S. Bell<sup>79</sup>, G. Bella<sup>153</sup>, L. Bellagamba<sup>22a</sup>, A. Bellerive<sup>31</sup>, M. Bellomo<sup>87</sup>, K. Belotskiy<sup>98</sup>, O. Beltramello<sup>32</sup>, N.L. Belyaev<sup>98</sup>, O. Benary<sup>153</sup>, D. Benchekroun<sup>135a</sup>, M. Bender<sup>100</sup>, K. Bendtz<sup>146a,146b</sup>, N. Benekos<sup>10</sup>, Y. Benhammou<sup>153</sup>, E. Benhar Noccioli<sup>175</sup>, J. Benitez<sup>64</sup>, D.P. Benjamin<sup>47</sup>, J.R. Bensinger<sup>25</sup>, S. Bentvelsen<sup>107</sup>, L. Beresford<sup>120</sup>, M. Beretta<sup>49</sup>, D. Berge<sup>107</sup>, E. Bergeaas Kuutmann<sup>164</sup>, N. Berger<sup>5</sup>, J. Beringer<sup>16</sup>, S. Berlendis<sup>57</sup>, N.R. Bernard<sup>87</sup>, C. Bernius<sup>110</sup>, F.U. Bernlochner<sup>23</sup>, T. Berry<sup>78</sup>, P. Berta<sup>129</sup>, C. Bertella<sup>84</sup>, G. Bertoli<sup>146a,146b</sup>, F. Bertolucci<sup>124a,124b</sup>, I.A. Bertram<sup>73</sup>, C. Bertsche<sup>44</sup>, D. Bertsche<sup>113</sup>, G.J. Besjes<sup>38</sup>, O. Bessidskaia Bylund<sup>146a,146b</sup>, M. Bessner<sup>44</sup>, N. Besson<sup>136</sup>, C. Betancourt<sup>50</sup>, S. Bethke<sup>101</sup>, A.J. Bevan<sup>77</sup>, R.M. Bianchi<sup>125</sup>, L. Bianchini<sup>25</sup>, M. Bianco<sup>32</sup>, O. Biebel<sup>100</sup>, D. Biedermann<sup>17</sup>, R. Bielski<sup>85</sup>, N.V. Biesuz<sup>124a,124b</sup>, M. Biglietti<sup>134a</sup>, J. Bilbao De Mendizabal<sup>51</sup>, T.R.V. Billoud<sup>95</sup>, H. Bilokon<sup>49</sup>, M. Bindi<sup>56</sup>, S. Binet<sup>117</sup>, A. Bingul<sup>20b</sup>, C. Bini<sup>132a,132b</sup>, S. Biondi<sup>22a,22b</sup>, D.M. Bjergaard<sup>47</sup>, C.W. Black<sup>150</sup>, J.E. Black<sup>143</sup>, K.M. Black<sup>24</sup>, D. Blackburn<sup>138</sup>, R.E. Blair<sup>6</sup>, J.-B. Blanchard<sup>136</sup>, T. Blazek<sup>144a</sup>, I. Bloch<sup>44</sup>, C. Blocker<sup>25</sup>, W. Blum<sup>84,\*</sup>,



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C. Unverdorben<sup>100</sup>, J. Urban<sup>144b</sup>, P. Urquijo<sup>89</sup>, P. Urrejola<sup>84</sup>, G. Usai<sup>8</sup>, A. Usanova<sup>63</sup>, L. Vacavant<sup>86</sup>, V. Vacek<sup>128</sup>, B. Vachon<sup>88</sup>, C. Valderanis<sup>100</sup>, E. Valdes Santurio<sup>146a,146b</sup>, N. Valencic<sup>107</sup>, S. Valentini<sup>22a,22b</sup>, A. Valero<sup>166</sup>, L. Valery<sup>13</sup>, S. Valkar<sup>129</sup>, J.A. Valls Ferrer<sup>166</sup>, W. Van Den Wollenberg<sup>107</sup>, P.C. Van Der Deijl<sup>107</sup>, H. van der Graaf<sup>107</sup>, N. van Eldik<sup>152</sup>, P. van Gemmeren<sup>6</sup>, J. Van Nieuwkoop<sup>142</sup>, I. van Vulpen<sup>107</sup>, M.C. van Woerden<sup>32</sup>, M. Vanadia<sup>132a,132b</sup>, W. Vandelli<sup>32</sup>, R. Vanguri<sup>122</sup>, A. Vaniachine<sup>130</sup>, P. Vankov<sup>107</sup>, G. Vardanyan<sup>176</sup>, R. Vari<sup>132a</sup>, E.W. Varnes<sup>7</sup>, T. Varol<sup>42</sup>, D. Varouchas<sup>81</sup>, A. 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Wang<sup>23</sup>, T. Wang<sup>37</sup>, W. Wang<sup>35b</sup>, X. Wang<sup>175</sup>, C. Wanotayaroj<sup>116</sup>, A. Warburton<sup>88</sup>, C.P. Ward<sup>30</sup>, D.R. Wardrope<sup>79</sup>, A. Washbrook<sup>48</sup>, P.M. Watkins<sup>19</sup>, A.T. Watson<sup>19</sup>, M.F. Watson<sup>19</sup>, G. Watts<sup>138</sup>, S. Watts<sup>85</sup>, B.M. Waugh<sup>79</sup>, S. Webb<sup>84</sup>, M.S. Weber<sup>18</sup>, S.W. Weber<sup>173</sup>, J.S. Webster<sup>6</sup>, A.R. Weidberg<sup>120</sup>, B. Weinert<sup>62</sup>, J. Weingarten<sup>56</sup>, C. Weiser<sup>50</sup>, H. Weits<sup>107</sup>, P.S. Wells<sup>32</sup>, T. Wenaus<sup>27</sup>, T. Wengler<sup>32</sup>, S. Wenig<sup>32</sup>, N. Wermes<sup>23</sup>, M. Werner<sup>50</sup>, M.D. Werner<sup>65</sup>, P. Werner<sup>32</sup>, M. Wessels<sup>59a</sup>, J. Wetter<sup>161</sup>, K. Whalen<sup>116</sup>, N.L. Whallon<sup>138</sup>, A.M. Wharton<sup>73</sup>, A. White<sup>8</sup>, M.J. White<sup>1</sup>, R. White<sup>34b</sup>, D. Whiteson<sup>162</sup>, F.J. Wickens<sup>131</sup>, W. Wiedenmann<sup>172</sup>, M. Wielers<sup>131</sup>, P. Wienemann<sup>23</sup>, C. Wiglesworth<sup>38</sup>, L.A.M. Wiik-Fuchs<sup>23</sup>, A. Wildauer<sup>101</sup>, F. Wilk<sup>85</sup>, H.G. Wilkens<sup>32</sup>, H.H. Williams<sup>122</sup>, S. Williams<sup>107</sup>, C. Willis<sup>91</sup>, S. Willocq<sup>87</sup>, J.A. Wilson<sup>19</sup>, I. Wingerter-Seez<sup>5</sup>, F. Winklmeier<sup>116</sup>, O.J. Winston<sup>149</sup>, B.T. Winter<sup>23</sup>, M. Wittgen<sup>143</sup>, J. Wittkowski<sup>100</sup>, T.M.H. Wolf<sup>107</sup>, M.W. Wolter<sup>41</sup>, H. Wolters<sup>126a,126c</sup>, S.D. Worm<sup>131</sup>, B.K. Wosiek<sup>41</sup>, J. Wotschack<sup>32</sup>, M.J. Woudstra<sup>85</sup>, K.W. Wozniak<sup>41</sup>, M. Wu<sup>57</sup>, M. Wu<sup>33</sup>, S.L. Wu<sup>172</sup>, X. Wu<sup>51</sup>, Y. Wu<sup>90</sup>, T.R. Wyatt<sup>85</sup>, B.M. Wynne<sup>48</sup>, S. Xella<sup>38</sup>, D. 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<sup>1</sup> Department of Physics, University of Adelaide, Adelaide, Australia

<sup>2</sup> Physics Department, SUNY Albany, Albany, NY, United States

<sup>3</sup> Department of Physics, University of Alberta, Edmonton, AB, Canada

<sup>4</sup> (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

<sup>5</sup> LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France

<sup>6</sup> High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States

<sup>7</sup> Department of Physics, University of Arizona, Tucson, AZ, United States

<sup>8</sup> Department of Physics, The University of Texas at Arlington, Arlington, TX, United States

<sup>9</sup> Physics Department, University of Athens, Athens, Greece

<sup>10</sup> Physics Department, National Technical University of Athens, Zografou, Greece



- <sup>11</sup> Department of Physics, The University of Texas at Austin, Austin, TX, United States
- <sup>12</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- <sup>13</sup> Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
- <sup>14</sup> Institute of Physics, University of Belgrade, Belgrade, Serbia
- <sup>15</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway
- <sup>16</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States
- <sup>17</sup> Department of Physics, Humboldt University, Berlin, Germany
- <sup>18</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- <sup>19</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- <sup>20</sup> <sup>(a)</sup> Department of Physics, Bogazici University, Istanbul; <sup>(b)</sup> Department of Physics Engineering, Gaziantep University, Gaziantep; <sup>(d)</sup> Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; <sup>(e)</sup> Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
- <sup>21</sup> Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- <sup>22</sup> <sup>(a)</sup> INFN Sezione di Bologna; <sup>(b)</sup> Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
- <sup>23</sup> Physikalisches Institut, University of Bonn, Bonn, Germany
- <sup>24</sup> Department of Physics, Boston University, Boston, MA, United States
- <sup>25</sup> Department of Physics, Brandeis University, Waltham, MA, United States
- <sup>26</sup> <sup>(a)</sup> Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; <sup>(b)</sup> Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; <sup>(c)</sup> Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; <sup>(d)</sup> Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
- <sup>27</sup> Physics Department, Brookhaven National Laboratory, Upton, NY, United States
- <sup>28</sup> <sup>(a)</sup> Transilvania University of Brasov, Brasov; <sup>(b)</sup> National Institute of Physics and Nuclear Engineering, Bucharest; <sup>(c)</sup> National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; <sup>(d)</sup> University Politehnica Bucharest, Bucharest; <sup>(e)</sup> West University in Timisoara, Timisoara, Romania
- <sup>29</sup> Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- <sup>30</sup> Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- <sup>31</sup> Department of Physics, Carleton University, Ottawa, ON, Canada
- <sup>32</sup> CERN, Geneva, Switzerland
- <sup>33</sup> Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
- <sup>34</sup> <sup>(a)</sup> Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; <sup>(b)</sup> Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- <sup>35</sup> <sup>(a)</sup> Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; <sup>(b)</sup> Department of Modern Physics, University of Science and Technology of China, Anhui; <sup>(c)</sup> Department of Physics, Nanjing University, Jiangsu; <sup>(d)</sup> School of Physics, Shandong University, Shandong; <sup>(e)</sup> Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai <sup>400</sup>; <sup>(f)</sup> Physics Department, Tsinghua University, Beijing 100084, China
- <sup>36</sup> Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- <sup>37</sup> Nevis Laboratory, Columbia University, Irvington, NY, United States
- <sup>38</sup> Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- <sup>39</sup> <sup>(a)</sup> INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; <sup>(b)</sup> Dipartimento di Fisica, Università della Calabria, Rende, Italy
- <sup>40</sup> <sup>(a)</sup> AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; <sup>(b)</sup> Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- <sup>41</sup> Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- <sup>42</sup> Physics Department, Southern Methodist University, Dallas, TX, United States
- <sup>43</sup> Physics Department, University of Texas at Dallas, Richardson, TX, United States
- <sup>44</sup> DESY, Hamburg and Zeuthen, Germany
- <sup>45</sup> Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- <sup>46</sup> Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- <sup>47</sup> Department of Physics, Duke University, Durham, NC, United States
- <sup>48</sup> SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- <sup>49</sup> INFN Laboratori Nazionali di Frascati, Frascati, Italy
- <sup>50</sup> Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- <sup>51</sup> Section de Physique, Université de Genève, Geneva, Switzerland
- <sup>52</sup> <sup>(a)</sup> INFN Sezione di Genova; <sup>(b)</sup> Dipartimento di Fisica, Università di Genova, Genova, Italy
- <sup>53</sup> <sup>(a)</sup> E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; <sup>(b)</sup> High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- <sup>54</sup> II Physikalisches Institut, Justus-Liebig-Universität Gießen, Gießen, Germany
- <sup>55</sup> SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- <sup>56</sup> II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- <sup>57</sup> Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
- <sup>58</sup> Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
- <sup>59</sup> <sup>(a)</sup> Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(b)</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(c)</sup> ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- <sup>60</sup> Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- <sup>61</sup> <sup>(a)</sup> Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; <sup>(b)</sup> Department of Physics, The University of Hong Kong, Hong Kong; <sup>(c)</sup> Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- <sup>62</sup> Department of Physics, Indiana University, Bloomington, IN, United States
- <sup>63</sup> Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- <sup>64</sup> University of Iowa, Iowa City, IA, United States
- <sup>65</sup> Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
- <sup>66</sup> Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- <sup>67</sup> KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- <sup>68</sup> Graduate School of Science, Kobe University, Kobe, Japan
- <sup>69</sup> Faculty of Science, Kyoto University, Kyoto, Japan
- <sup>70</sup> Kyoto University of Education, Kyoto, Japan
- <sup>71</sup> Department of Physics, Kyushu University, Fukuoka, Japan
- <sup>72</sup> Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- <sup>73</sup> Physics Department, Lancaster University, Lancaster, United Kingdom
- <sup>74</sup> <sup>(a)</sup> INFN Sezione di Lecce; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- <sup>75</sup> Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- <sup>76</sup> Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- <sup>77</sup> School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- <sup>78</sup> Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- <sup>79</sup> Department of Physics and Astronomy, University College London, London, United Kingdom
- <sup>80</sup> Louisiana Tech University, Ruston, LA, United States
- <sup>81</sup> Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

- <sup>82</sup> Fysiska Institutionen, Lunds Universitet, Lund, Sweden
- <sup>83</sup> Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- <sup>84</sup> Institut für Physik, Universität Mainz, Mainz, Germany
- <sup>85</sup> School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- <sup>86</sup> CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- <sup>87</sup> Department of Physics, University of Massachusetts, Amherst, MA, United States
- <sup>88</sup> Department of Physics, McGill University, Montreal, QC, Canada
- <sup>89</sup> School of Physics, University of Melbourne, Victoria, Australia
- <sup>90</sup> Department of Physics, The University of Michigan, Ann Arbor, MI, United States
- <sup>91</sup> Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
- <sup>92</sup> (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- <sup>93</sup> B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- <sup>94</sup> National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
- <sup>95</sup> Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- <sup>96</sup> P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- <sup>97</sup> Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- <sup>98</sup> National Research Nuclear University MEPhI, Moscow, Russia
- <sup>99</sup> D.V. Skobel'syn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- <sup>100</sup> Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- <sup>101</sup> Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- <sup>102</sup> Nagasaki Institute of Applied Science, Nagasaki, Japan
- <sup>103</sup> Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- <sup>104</sup> (a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- <sup>105</sup> Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
- <sup>106</sup> Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- <sup>107</sup> Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- <sup>108</sup> Department of Physics, Northern Illinois University, DeKalb, IL, United States
- <sup>109</sup> Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- <sup>110</sup> Department of Physics, New York University, New York, NY, United States
- <sup>111</sup> Ohio State University, Columbus, OH, United States
- <sup>112</sup> Faculty of Science, Okayama University, Okayama, Japan
- <sup>113</sup> Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
- <sup>114</sup> Department of Physics, Oklahoma State University, Stillwater, OK, United States
- <sup>115</sup> Palacký University, RCPTM, Olomouc, Czech Republic
- <sup>116</sup> Center for High Energy Physics, University of Oregon, Eugene, OR, United States
- <sup>117</sup> LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- <sup>118</sup> Graduate School of Science, Osaka University, Osaka, Japan
- <sup>119</sup> Department of Physics, University of Oslo, Oslo, Norway
- <sup>120</sup> Department of Physics, Oxford University, Oxford, United Kingdom
- <sup>121</sup> (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- <sup>122</sup> Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
- <sup>123</sup> National Research Centre "Kurchatov Institute" B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- <sup>124</sup> (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- <sup>125</sup> Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
- <sup>126</sup> (a) Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Department of Physics, University of Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Física, Universidade do Minho, Braga; (f) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); (g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- <sup>127</sup> Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- <sup>128</sup> Czech Technical University in Prague, Praha, Czech Republic
- <sup>129</sup> Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- <sup>130</sup> State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
- <sup>131</sup> Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- <sup>132</sup> (a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- <sup>133</sup> (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- <sup>134</sup> (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- <sup>135</sup> (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; (b) Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V, Rabat, Morocco
- <sup>136</sup> DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- <sup>137</sup> Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
- <sup>138</sup> Department of Physics, University of Washington, Seattle, WA, United States
- <sup>139</sup> Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- <sup>140</sup> Department of Physics, Shinshu University, Nagano, Japan
- <sup>141</sup> Fachbereich Physik, Universität Siegen, Siegen, Germany
- <sup>142</sup> Department of Physics, Simon Fraser University, Burnaby, BC, Canada
- <sup>143</sup> SLAC National Accelerator Laboratory, Stanford, CA, United States
- <sup>144</sup> (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- <sup>145</sup> (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- <sup>146</sup> (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
- <sup>147</sup> Physics Department, Royal Institute of Technology, Stockholm, Sweden
- <sup>148</sup> Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States
- <sup>149</sup> Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- <sup>150</sup> School of Physics, University of Sydney, Sydney, Australia
- <sup>151</sup> Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>152</sup> Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- <sup>153</sup> Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- <sup>154</sup> Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

- <sup>155</sup> International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan  
<sup>156</sup> Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan  
<sup>157</sup> Department of Physics, Tokyo Institute of Technology, Tokyo, Japan  
<sup>158</sup> Department of Physics, University of Toronto, Toronto, ON, Canada  
<sup>159</sup> <sup>(a)</sup> TRIUMF, Vancouver, BC; <sup>(b)</sup> Department of Physics and Astronomy, York University, Toronto, ON, Canada  
<sup>160</sup> Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan  
<sup>161</sup> Department of Physics and Astronomy, Tufts University, Medford, MA, United States  
<sup>162</sup> Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States  
<sup>163</sup> <sup>(a)</sup> INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; <sup>(b)</sup> ICTP, Trieste; <sup>(c)</sup> Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy  
<sup>164</sup> Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden  
<sup>165</sup> Department of Physics, University of Illinois, Urbana, IL, United States  
<sup>166</sup> Instituto de Física Corpuscular (IFIC) and Departamento de Física Atomica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain  
<sup>167</sup> Department of Physics, University of British Columbia, Vancouver, BC, Canada  
<sup>168</sup> Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada  
<sup>169</sup> Department of Physics, University of Warwick, Coventry, United Kingdom  
<sup>170</sup> Waseda University, Tokyo, Japan  
<sup>171</sup> Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel  
<sup>172</sup> Department of Physics, University of Wisconsin, Madison, WI, United States  
<sup>173</sup> Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany  
<sup>174</sup> Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany  
<sup>175</sup> Department of Physics, Yale University, New Haven, CT, United States  
<sup>176</sup> Yerevan Physics Institute, Yerevan, Armenia  
<sup>177</sup> Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

- <sup>a</sup> Also at Department of Physics, King's College London, London, United Kingdom.  
<sup>b</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.  
<sup>c</sup> Also at Novosibirsk State University, Novosibirsk, Russia.  
<sup>d</sup> Also at TRIUMF, Vancouver BC, Canada.  
<sup>e</sup> Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States of America.  
<sup>f</sup> Also at Department of Physics, California State University, Fresno CA, United States of America.  
<sup>g</sup> Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.  
<sup>h</sup> Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.  
<sup>i</sup> Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal.  
<sup>j</sup> Also at Tomsk State University, Tomsk, Russia.  
<sup>k</sup> Also at Università di Napoli Parthenope, Napoli, Italy.  
<sup>l</sup> Also at Institute of Particle Physics (IPP), Canada.  
<sup>m</sup> Also at National Institute of Physics and Nuclear Engineering, Bucharest, Romania.  
<sup>n</sup> Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.  
<sup>o</sup> Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America.  
<sup>p</sup> Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.  
<sup>q</sup> Also at Louisiana Tech University, Ruston LA, United States of America.  
<sup>r</sup> Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.  
<sup>s</sup> Also at Graduate School of Science, Osaka University, Osaka, Japan.  
<sup>t</sup> Also at Department of Physics, National Tsing Hua University, Taiwan.  
<sup>u</sup> Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.  
<sup>v</sup> Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America.  
<sup>w</sup> Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.  
<sup>x</sup> Also at CERN, Geneva, Switzerland.  
<sup>y</sup> Also at Georgian Technical University (GTU), Tbilisi, Georgia.  
<sup>z</sup> Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.  
<sup>aa</sup> Also at Manhattan College, New York NY, United States of America.  
<sup>ab</sup> Also at Hellenic Open University, Patras, Greece.  
<sup>ac</sup> Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.  
<sup>ad</sup> Also at School of Physics, Shandong University, Shandong, China.  
<sup>ae</sup> Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.  
<sup>af</sup> Also at Section de Physique, Université de Genève, Geneva, Switzerland.  
<sup>ag</sup> Also at Eotvos Lorand University, Budapest, Hungary.  
<sup>ah</sup> Also at Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America.  
<sup>ai</sup> Also at International School for Advanced Studies (SISSA), Trieste, Italy.  
<sup>aj</sup> Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America.  
<sup>ak</sup> Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.  
<sup>al</sup> Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.  
<sup>am</sup> Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.  
<sup>an</sup> Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.  
<sup>ao</sup> Also at National Research Nuclear University MEPhI, Moscow, Russia.  
<sup>ap</sup> Also at Department of Physics, Stanford University, Stanford CA, United States of America.  
<sup>aq</sup> Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.  
<sup>ar</sup> Also at Flensburg University of Applied Sciences, Flensburg, Germany.  
<sup>as</sup> Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.  
<sup>at</sup> Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.  
<sup>au</sup> Also affiliated with PKU-CHEP.  
<sup>\*</sup> Deceased.